

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26

MICROMACHINED VERTICAL VIBRATING GYROSCOPE

Field of the Invention

The present invention relates to a micromachined gyroscope and more particularly, to a micromachined gyroscope performing lateral sensing of angular rates, having both driving and sensing oscillation modes, and having all components formed from a single silicon crystal of a single silicon wafer.

Background of the Invention

Gyroscopes are used to measure the angular deviation of a guided missile from its desired flight trajectory; to determine the heading of a vehicle for steering; to determine the heading of an automobile as it turns; to indicate the heading and orientation of an airplane during and after a series of maneuvers; or to stabilize and point radar dishes and satellites. Recently, micromachined gyroscopes are receiving increasing attention because of their low cost, small size and high sensitivity. Micromachined vertical or z-axis gyroscopes are used to counteract the rolling effect on a vehicle, and thus, are a preferred stabilization tool for vehicles such as airplanes, ships, and cars.

One developed micromachined vertical gyroscope utilizes a rapidly spinning, heavy mass. These spinning mass gyroscopes require lubrication and eventually wear out.

Another developed micromachined vertical gyroscope is based on vibration mode, but uses polysilicon technology. All suspension structures of this gyroscope are made of a polysilicon layer. To release the suspension structures a thick sacrificial layer is applied beneath the polysilicon layer. After the polysilicon layer is etched through, the sacrificial layer is removed. There are several problems with this gyroscope.

Although a single crystal silicon wafer may be used as a substrate of the gyroscope, the single crystal silicon wafer with several additional layers thereon is no longer suitable for standard microelectronics processing to realize monolithic integration.

1 An as-deposited polysilicon layer is in compressive strain. Suspension structures
2 formed from the strain polysilicon layer tend to buckle, causing gyroscope instability or
3 inability to work.

4 Since the surface of a relatively thick polysilicon layer is quite rough an additional
5 polishing step is required before a planar processing process.

6 It is impossible to deposit a relatively thick polysilicon layer with device quality. This
7 limits the stiffness of the suspension flexures in the vertical direction and makes electrostatic
8 comb drive levitation more difficult to control.

9 SUMMARY OF THE INVENTION

10 Accordingly, it is an object of the present invention to provide a micromachined vertical
11 vibrating gyroscope with all suspension structures being of single crystal silicon. The use of
12 single crystal silicon structure eliminates the problems of the prior art caused by utilizing
13 polysilicon as a building material.

14 It is a further object of the present invention to provide a micromachined vertical
15 vibrating gyroscope with all suspension structures recessed into a processed silicon wafer.
16 These recessed structures are more robust than any structures being out of the plane of the
17 processed silicon wafer.

18 It is a still further object of the present invention to provide a micromachined vertical
19 vibrating gyroscope capable of being produced by processing a single silicon wafer. Since
20 no other wafer is required, the process is simple and allows batch production.

21 It is a still further object of the present invention to provide a micromachined vertical
22 vibrating gyroscope capable of being fabricated on a single processing plane all along. This
23 facilitates the use of standard planar processing technologies for integrated circuits.

24 A still further object of the present invention to provide a micromachined vertical
25 vibrating gyroscope capable of being electronically integrated with other electronics similarly
26 fabricated on the same chip so as to realize monolithic integration.

1 In accordance with these and other objects, a micromachined vertical vibrating
 2 gyroscope is described. The gyroscope consists of three single crystal silicon assemblies: an
 3 outer single crystal silicon assembly, an intermediate single crystal silicon assembly, and an
 4 inner single crystal silicon assembly. The outer assembly includes a plurality of arc-shaped
 5 anchors arranged in a circle and extending from a single crystal silicon substrate coated with
 6 an insulating annulus thereon. Each of at least four anchors support a suspension flexure and
 7 two suspension fan-shaped stops on its inner edge. The intermediate assembly is a
 8 suspension wheel possessing a same center with the circle and having a plurality of combs
 9 protruding from its outer edge. The linkage between the outer assembly and the intermediate
 10 assembly is realized through the four suspension flexures arranged along two orthogonal
 11 axes. The inner assembly is a suspension hub possessing a same center with the circle and
 12 no axle at its center. The linkage between the intermediate assembly and the inner assembly
 13 is realized through other two flexures arranged along a same axis. The intermediate
 14 suspension wheel is driven into rotational vibration by lateral comb capacitors. Each lateral
 15 comb capacitor is formed by a combination of a comb protruding from an anchor and a comb
 16 protruding from the intermediate wheel. Input angular rates are measured by two vertical
 17 capacitors that are formed between the bottom of the inner suspension hub and the interior
 18 top surface of the substrate used to support the anchors.

19 The micromachined vertical vibrating gyroscope is fabricated utilizing a bipolar-
 20 compatible process. This process comprises the steps of forming a buried layer, depositing
 21 and patterning an insulation layer, and growing an epitaxial layer. The epitaxial layer grown
 22 on the buried layer is of single crystal silicon and on the insulation layer is of lateral overgrown
 23 single crystal silicon. After converting the buried layer into a porous silicon layer all
 24 suspension structures are formed by partially etching into the epitaxial layer and removing the
 25 beneath porous silicon layer. The rest of the porous silicon layer is turned into an oxidized
 26 porous silicon layer for electrically isolating the anchors located thereon.

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 Fig. 1 is a partially cut away perspective view of a micromachined vertical vibrating
3 gyroscope in accordance with the present invention;

4 Fig. 2 is a cross-sectional view of a buried layer formed in a single crystal silicon
5 substrate for fabricating the vertical vibrating gyroscope of Fig. 1 in accordance with the
6 present invention;

7 Fig. 3 is a cross-sectional view of an epitaxial single crystal silicon layer formed on the
8 silicon exposed regions of the single crystal silicon substrate and a lateral overgrowth single
9 crystal layer formed on an insulating ring of the single crystal silicon substrate for fabricating
10 the vertical vibrating gyroscope of the figure 1 in accordance with the present invention;

11 Figs. 4A and 4B are cross-sectional views showing an empty trench formed in the
12 epitaxial single crystal silicon layer and showing an etch depth indication cavity formed in the
13 lateral overgrowth single crystal silicon layer for fabricating the vertical vibrating gyroscope
14 of Fig. 1 in accordance with the present invention;

15 Fig. 5 is a cross-sectional view of an insulating material filled trench formed in the
16 epitaxial single crystal silicon layer for fabricating the vertical vibrating gyroscope of Fig. 1 in
17 accordance with the present invention;

18 Fig. 6 is a cross-sectional view of a plurality of empty trenches formed in the epitaxial
19 single crystal silicon layer for fabricating the vertical vibrating gyroscope of Fig. 1 in
20 accordance with the present invention;

21 Fig. 7 is a cross-sectional view of a porous silicon layer replacing the buried layer for
22 fabricating the vertical vibrating gyroscope of Fig. 1 in accordance with the present invention;

23 Fig. 8 is a cross-sectional view of a plurality of suspension structures formed by
24 partially removing the porous silicon layer and an oxidized porous silicon layer replacing the
25 rest of the porous silicon layer for fabricating the vertical vibrating gyroscope of Fig. 1 in
26 accordance with the present invention;

1 Fig. 9 is a cross-sectional view of a heavily doped diffusion layer formed on the
2 surfaces of the suspension structures for fabricating the vertical vibrating gyroscope of Fig.
3 1 in accordance with the present invention;

4 Fig. 10 is a cross-sectional view of an insulating layer coated on the diffusion layer for
5 fabricating the vertical vibrating gyroscope of Fig. 1 in accordance with the present invention;
6 and

7 Fig. 11 is a cross-sectional view of a metal layer deposited on the sidewalls of the
8 suspension structures for fabricating the vertical vibrating gyroscope of Fig. 1 in accordance
9 with the present invention.

10 DETAILED DESCRIPTION OF THE INVENTION

11 Referring now to Fig. 1, a micromachined vertical vibrating gyroscope 10 includes a
12 single crystal silicon substrate 11 with an epitaxial layer thereon. The epitaxial layer includes
13 three regions: an outer periphery region, an intermediate ring region 18, and an inner circle
14 or hub region 23. The outer periphery region is originally grown from the surface of the
15 substrate, but later the beneath layer turns into an oxidized porous silicon layer 15; an outer
16 ring region 14 is extended from beneath insulating ring 13 that is coated on the surface of the
17 substrate 11. The inner circle region (hub 23) also is originally grown from the surface of the
18 substrate 11, but later the beneath layer is removed to leave an air gap 24 therein. The whole
19 epitaxial layer including the intermediate ring region 18 is single crystal silicon with same
20 crystalline properties as the substrate 11. Also shown are a plurality of arc-shaped anchors
21 12 that are arranged in a circle and each having several through holes 16 therein, an
22 intermediate vibrating wheel 18 that has a same center with the circle formed by anchors 12,
23 and an inner vibrating hub 23 that also has the same center with the circle formed by anchors
24 12. The arc-shaped anchors 12 form a circle that is concentric with the circles formed by the
25 intermediate vibrating wheel and hub 23.

26

1 Each of the arc-anchors 12 comprises of an outer portion and an inner portion. The
2 outer portion is made of the outer periphery region of the epitaxial layer that is disposed on
3 the oxidized porous silicon layer 15. The inner portion is made of the ring region of the
4 epitaxial layer that is disposed on the insulating ring 13.

5 There are at least four anchors 12, each supporting a suspended single-crystal silicon
6 flexure 20 and two suspended and perforated fan-shaped single crystal silicon mechanical
7 stops 22 that sandwich the flexure 20. Each of the rest anchors supports a suspended single
8 crystal silicon comb 17 with a plurality of side fingers extending from its one side.

9 The flexures 20 are arranged to align with the coordinate x-axis and y-axis,
10 respectively, which are set on the substrate plane. The aspect ratio of the flexures 20 is
11 relatively high so that they are stiff in response to the vertical motion and flexible in response
12 to the lateral motion. With these features the wheel 18 is easy to stimulate to rotate about the
13 vertical axis or the coordinate z-axis, but not to move along the coordinate x-axis and y-axis,
14 and rotate about the coordinate x-axis and y-axis.

15 The wheel 18 is made of the inner circle region of the epitaxial layer that is separated
16 from the substrate 11 by the air gap 24. Along the central line there are two insulating
17 trenches 19 to divide the wheel 18 into two area-equal half-wheels. The four flexures 20 join
18 the wheel 18 and the anchors 12 so that the anchors 12 indirectly support the wheel 18. There
19 are at least eight suspended single crystal silicon combs 21 extending from the outer edge
20 of the wheel 18 so that each two of which sandwich an adjacent two comb 17. The combs 21
21 also have a plurality of side fingers extending from their one side. Each comb 21 combines
22 with a comb 17 so that their side fingers are interdigitated.

23 The hub 23 is also made of the inner circle region of the epitaxial layer that is
24 separated from the substrate 11 by the air gap 24. Along a zigzag line there are insulating
25 trenches 25 to divide the hub 23 into two area-equal half-hubs. A plurality of damping holes
26 26 are scattered in the hub 23. There are also two suspended single crystal silicon flexures

1 27 that join the wheel 18 and the hub 23 so that the anchors 12 also indirectly support the
2 hub 23.

3 The flexures 27 are arranged along the extending direction of the central symmetric line
4 of the hub 23. One flexure 27 electrically connects a half-hub to two outer bonding pads 34
5 and 35. The other flexure 27 (not shown in the figure) electrically connects the other half-hub
6 to other two bonding pads (not shown in the figure). The bonding pads are disposed on the
7 anchors 12 that are electrically isolated from the substrate 11 by the insulating ring 13 and
8 the oxidized porous silicon layer 15. The geometric shape of the flexures 27 is designed to
9 be stiff in response to the vertical motion of the hub 23 and flexible in response to the rotation
10 of the hub 23 about their longitudinal direction.

11 The micromachined vertical vibrating gyroscope 10 further comprises at least four
12 lateral driving capacitors 28 and four lateral monitoring capacitors 29. The lateral drive
13 capacitors 28 and the lateral monitoring capacitors 29 are located in four symmetric fan-
14 shaped regions. Each fan-shaped region contains a lateral driving capacitor and a lateral
15 monitoring capacitor. Each lateral capacitor for driving or monitoring of the vibration of the
16 wheel 18 consists of two combs. One comb extends from an anchor 12 and the other comb
17 extends from the wheel 18. The fingers of the two combs are interdigitated with each other so
18 that each two opposite fingers are faced sidewall to sidewall.

19 The micromachined vertical vibrating gyroscope 10 further comprises two vertical
20 measuring capacitors 32 and 33. The vertical measuring capacitors are formed from the
21 electrodes attached to the bottom of the hub 23 and to the inner top surface of the substrate
22 11 respectively. The hub 23 is electrically divided into two area-equal half-hubs by the
23 insulating trench 25. Each half-hub has an independent electrode attached thereon and
24 electrically connects to two shown outer bonding pads 34 and 35 or other two un-shown outer
25 bonding pads through the shown flexure 27 or the other un-shown flexure.

26

1 The electrodes of the vertical measuring capacitors 32 and 33 are formed from a
2 diffusion layer disposed on the bottom surface of the wheel 23 and the top surface of the
3 substrate 11. Different from this, the electrodes of the lateral capacitors 28 and 29 are formed
4 from a metal layer deposited on the sidewalls of the figures of the combs 17 and 21. An
5 insulating layer separates these two kinds of the electrodes (not shown in Fig. 1). Even though
6 both the electrodes of the vertical capacitors 32 and 33 and the lateral capacitors 28 and 29
7 have common supporting silicon structures they are electrically isolated by this insulating
8 layer.

9 Under the inner portion of each anchor 12 there is a cavity with the insulating ring 13
10 on its top. It can be seen that the cavity has two functions. The first function is to prevent the
11 two diffusion layers of the electrodes of the vertical capacitors 32 and 33 from joining together
12 at this point. The second function is to stop the metal layer of the electrodes of the lateral
13 capacitors 28 and 29 to continuously extend to the interior top surface of the substrate 11.
14 Because of this, the lateral capacitors 28 and 29 and vertical capacitors 32 and 33 can be
15 electrically isolated each other.

16 In operation of the micromachined vertical vibrating gyroscope 10 a voltage is applied
17 to the lateral driving capacitors 28. The intermediate wheel 18 is then stimulated into
18 rotational vibration about the coordinate z-axis that is set to be vertical to the substrate plane.
19 For the rotational vibration of the wheel 18, the flexures 20 provide flexible mechanical
20 support. As the rotational angular becomes too large the stops 22 begin to abate the vibration
21 so as to prevent the flexures 20 from damaging. The lateral monitoring capacitors 29 is used
22 to measure the frequency and amplitude of the rotational vibration of the wheel 18. When the
23 substrate 11 experiences an angular rate about the coordinate x-axis that is set to be
24 perpendicular to the flexures 27 a Coriolis force is induced. The Coriolis force exerts on the
25 inner vibrating hub 23 and causes the hub 23 to be rotationally vibrated about the coordinate
26 y-axis.

1 In the balance state the two vertical capacitors 32 and 33 are designed to be
 2 completely equal. When the hub 23 rotates about the coordinate y-axis, the two vertical
 3 capacitors 32 and 33 are no longer equal. If the hub 23 rotates counterclockwise, the
 4 capacitance of the vertical capacitor 33 will increase and the capacitance of the vertical
 5 capacitor 32 will decrease. If the rotation direction reverses, the difference of the capacitance
 6 also reverses. Since the difference of the capacitance of the two vertical capacitors 32 and
 7 33 depends upon the input angular rate, the input angular rate can be determined by
 8 measuring the difference of the capacitance of the two vertical capacitors 32 and 33.

9 The measurement circuit can be adopted in open loop or in close loop. In open loop
 10 the amplitude of a carrier signal can be modulated by the difference of the capacitance of the
 11 two vertical capacitors 32 and 33. After demodulation with the carrier frequency and the
 12 driving signal frequency a DC voltage proportional to the input angular rate can be yielded as
 13 the output of the measurement circuit. In close loop the yielded signal is first fed to a
 14 rebalance circuit. The rebalance circuit then provides a rebalance voltage applying to the
 15 vertical capacitors 32 and 33 to null the rotation of the inner vibrating hub 23 about the
 16 coordinate y-axis. The rebalance voltage is proportional to the input angular rate.

17 The micromachined vertical vibrating gyroscope 10 is fabricated, in accordance with
 18 the present invention, utilizing a bipolar compatible process. In this process surface
 19 micromachining can be carried out as a number of post-processing steps after completion of
 20 a standard bipolar process. The bipolar compatible process, which is diagrammatically
 21 illustrated in Figs. 2-11, begins with a single crystal silicon wafer used as a substrate 101, as
 22 shown in Fig. 2. The substrate 101 is an (100) n-type silicon wafer with a resistivity ranging
 23 from 1 to 10 ohm-cm, typically being 3 ohm-cm. A 1 micron-thick silicon dioxide layer 102 is
 24 thermally grown on the surface of the substrate 101. Photolithography is used to pattern the
 25 silicon dioxide layer 102, and then a heavily doped buried n-type or p-type layer 103 is formed
 26 in the substrate 101 by thermal diffusion or a combination of ion implantation and thermal

Turning now to Figs. 4A and 4B, these figures illustrate the fabrication process of the insulating trenches of Fig. 1. The trenches 108 and 110 shown in Figs. 4A and 4B are cut from the processed substrate shown in Fig. 3. Fig. 4A shows the substrate 101, buried layer 103, insulating ring 104, epitaxial layer 105, and lateral overgrowth layer 106. The processed substrate shown in Fig. 4B already contains the substrate 101, buried layer 103, and epitaxial layer 105. As the first step for the fabrication process, a silicon dioxide layer 107 is formed by thermal oxidization on the surface of the epitaxial layer 105 and the lateral overgrowth layer 106. Then the silicon dioxide layer 107 is patterned to create silicon-exposed windows therein.

The next step is to perform deep reactive ion etching (DRIE) using the patterned silicon dioxide layer 107 as a protection mask. As shown in Fig. 5, the formed empty trench 110 is required to lower through the epitaxial layer 105 and reach the buried layer 103. For this purpose, an etch monitoring cavity 108 is created, as shown in Fig. 4A. As the etching goes on, the insulating ring 104 is first exposed on the bottom of the cavity 108 and then an etch step 109 is formed at the edge of the insulating ring 104. The height of the etch step 109 is used as an indication of the etch end. The width of the empty trench 110 ranges from 1 to 3 micron, typically is 2 micron. The width of the cavity 108 may be varied between 50 and 200 micron, typically is 100 micron. The cavity 108 is preferably located in the central region of the processed substrate.

As shown in Fig. 5, the empty trench 110 is turned into a filled trench 113 by being filled up with silicon nitride and polysilicon. The nitride layer 111 is deposited by low pressure chemical vapor deposition (LPCVD). Since LPCVD is a conformable coating the inside surface of the empty trench 110 can be covered uniformly. The thickness of the silicon nitride layer 111 ranges from 800 to 2000 angstrom, typically is 1000 angstrom. The polysilicon layer 112 is deposited also by LPCVD. The thickness of the polysilicon layer 112 is little larger than a half width of the empty trench 110 so that the empty trench is filled up completely.

1 It should be noted that, although the filled trench 113 of Fig. 5 only corresponds to the
2 insulating trench 25 of Fig. 1, the insulating trench 19 of Fig. 1 is formed in the same process.

3 The continuing step, as shown in Fig. 6, is to perform DRIE again to create a plurality
4 of trenches in the epitaxial layer 105. To do this a silicon dioxide layer 114 is deposited by
5 LPCVD. Then photolithography is used to pattern the stack layer of the silicon nitride layer
6 111, polysilicon layer 112, and silicon dioxide layer 114 for creating silicon-exposed windows
7 therein. Using the patterned stack layer as a protection mask, a DRIE process is carried out.
8 This process is to create trenches 115 and 116 that pass through the epitaxial layer 105 and
9 reach the buried layer 103.

10 It should be noted that for this process another etch monitoring cavity (not shown in the
11 figure) is used to accurately control the depth of the etching.

12 As shown in Fig. 7, the next step is to convert the buried layer 103 into a porous silicon
13 layer 117. Since the buried layer 103 is heavily doped it is preferable to anodize in HF
14 solution than lightly doped substrate 101 and lightly doped epitaxial layer 105 and lateral
15 overgrowth layer 106.

16 The used HF solution consists of one third of HF, one third of ethanol and one third
17 of water. The used etching apparatus consists of a double tank cell separated by the
18 processed substrate. For the process the two volumes of the HF solution are individually
19 contacted by Pt grids. The front side surface of the processed substrate faces the
20 cathodically biased grid while the rear surface faces the anodically biased grid in the other
21 tank.

22 It should be noted that a plurality of through holes in the inner hub 23 of Fig. 1 provide
23 entries for the HF solution to attack the buried layer 103 so as to shorten the lateral
24 anodization path and reduce the anodization time.

25 After forming porous silicon in selected areas of the processes substrate, a photoresist
26 layer 118 is applied to cover the trenches 116. Then the processed substrate is immersed into

a diluted KOH solution (1% KOH in H₂O) at room temperature to remove the porous silicon layer 117 in the selective area. This results in suspension components 121, 122, 123, air gap 119, and cavity 120, as shown in Fig. 8.

It should be noted that the suspension components 121, 122, 123 only correspond to the fingers of the combs 17, the immediate vibrating wheel 18, and the inner vibrating hub 23 of Fig. 1, the other suspension structures of Fig. 1, which are not shown in Fig. 8, are also formed in the same process.

After forming the suspension structures, a thin heavily doped diffusion layer 124 is formed on the surfaces of the suspension structures, as shown in Fig. 9. The diffusion process comprises of pre-deposition with POCl₃ at 950°C for 30 min and post-diffusion at a temperature ranging from 900 to 1000°C, typically 950°C in oxygen atmosphere for 30 min. During the diffusion step the porous silicon layer 117 is turned into an oxidized porous silicon layer 125. The oxidized porous silicon is similar to the silicon dioxide and can be used as an electrically insulating material.

It should be noted that the insulating ring 104 of the cavity 120 separates the diffusion layer 124 into two independence portions: one portion disposed on the bottom of the suspension structures and the other portion disposed on the interior top surface of the substrate 101.

It also should be noted that a plurality of through holes in the inner hub 23 of the figure 1 exist to make the diffusion layer 124 of Fig. 9 more uniform on the bottom of the hub 23 of Fig. 1.

Next, a silicon nitride layer 126 is deposited by LPCVD to coat the surfaces of the suspension structures, as shown in Fig. 10.

Thereafter, a metal layer 127, such as an aluminum layer is deposited by sputtering on the surfaces of the suspension structures. Since sputtering does not achieve conformal coating the aluminum layer 127 only forms on the top surfaces and sidewalls of the

1 suspension structures, as shown in Fig. 11. Therefore, there is no aluminum layer on the
2 bottom of the insulating ring 104.

3 It should be noted that the suspension structures are coated with three layers thereon:
4 the bottom diffusion layer 124, immediate silicon nitride layer 126, and top aluminum layer
5 127. The bottom diffusion layer 124 and top aluminum layer 127 are conduction layers, but
6 they are not electrically connected due to the immediate silicon nitride layer 126 inserted
7 between them.

8 Although the present invention has been disclosed in terms of the preferred
9 embodiments, it will be understood that modifications and variations can be made without
10 departing from the true spirit and scope thereof, as set forth in the following claims.

11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26